Evanescent Waves at the Interface between Ear Canal and Otoacoustic Emission Probe

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Abstract: The measurement of otoacoustic emissions (OAE) allows for an objective examination of the cochlear function. However, the validity of OAE tests is affected negatively by calibration errors, rendering the diagnosis less accurate. In this report, we shed light on the evanescent waves arising at the interface between the OAE probe and the ear canal. For this purpose, finite element models of the ear canal along with the microphone and sound tubes of the OAE probe were created. The impact of evanescent waves on the estimation of the acoustic length was studied. This effect was negligible for an average human ear canal model (8 mm diameter). However, for a 12 mm-diameter ear canal model, an extension of the probe microphone tube by 2 mm was required to counterbalance the evanescent wave effect. Hence, as a preliminary result, we expect that modifying the 12 mm-diameter eartips – by extending the probe microphone tube by about 2 mm – will have a positive effect on the length estimation of large-diameter ear canals.

Keywords: Evanescent wave, ear canal model, otoacoustic emission probe, eartip

1. Introduction

Otoacoustic emission (OAE) tests provide an objective, non-invasive and fast examination of the inner ear function [6]. These signals, generated within the cochlea as a response to well-specified acoustic stimuli, travel backwards to the ear canal (EC) where they can be detected by a small microphone in the OAE probe. Requiring no active collaboration from the patient, OAEs have become an indispensable test for neonates (Figure 1). However, OAE tests are subject to calibration errors [2] that affect this objective diagnosis.

Near-field (evanescent) waves arise at the interface between the EC and the probe due to the "flow" of sound between the small-diameter probe tubes and the EC, which has a considerably larger diameter (see Figure 2 in Section 2.1). The effect of evanescent waves on the sound pressure level (SPL) recorded by the probe microphone was deemed negligible (< 3 dB), should the sound- and microphone-tube ports be more than 2 mm apart [1]. However, the boundaries of the two sound tubes of the Etymotic Research ER-10C OAE probe [3] are hardly 1 mm away from those of the microphone tube (refer to Section 2.1). Hence, the microphone-tube port of the ER-10C OAE probe was extended by 4 mm [5] to avoid the problem of evanescent waves.

Figure 1. OAE probe inserted into a baby's ear canal for "Hearing Screening". Picture reproduced with kind permission of *Mack Medizintechnik GmbH*.

In this study, we question whether minor modifications in the eartip geometry may help bypass the evanescent waves at the interface between the EC and the OAE probe. First we investigated whether the microphone-tube extension, undertaken in [5], is generally applicable, irrespective of the EC diameter. Then we analysed whether extending one of the sound tubes of the OAE probe can be similarly applied. 3D finite element (FE) simulations were performed for this purpose.

2. Methods

2.1 Ear canal models

Two FE EC models (A and B) were simulated as acoustically rigid cavities using COMSOL Multiphysics. The EC models had the same physical length ($l_A = l_B = 25$ mm) but different diameters ($d_A = 8$ mm, $d_B = 12$ mm). The microphone tube (inner diameter i.d. = 2 mm) and the two sound tubes (i.d. = 0.7 mm) of the ER-10C OAE probe were modelled as rigid tubes having a length of 18 mm [4]. Similarly, the EC walls and the foam eartip [7] were modelled as acoustically rigid boundaries.

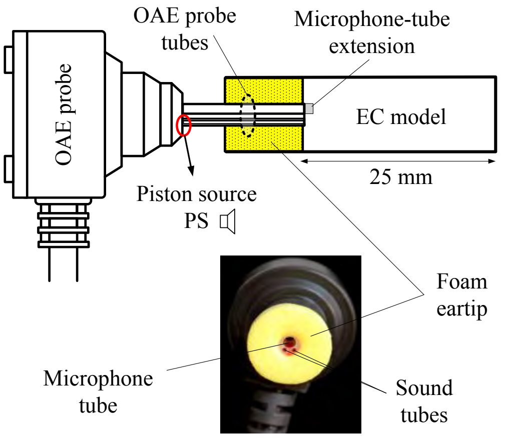

Figure 2. Top: 2D schematic of an OAE probe coupled to an EC model. A piston source (PS) feeds one sound tube. The microphone-tube extension is illustrated at the EC orifice. Bottom: Frontal picture of the ER-10C OAE probe.

A piston source (PS) producing a volume velocity ($q_0 = 0.8$ mm^3/s) was simulated at the probe end of the sound tube (see Figure 2), and the SPL was analysed at the microphone port.

The mesh dimensions, representing the EC geometry, were less than 1/6 of the wavelength for the frequency range under study (up to 8 kHz), and the frequency resolution was set to 10 Hz.

2.2 Eartip modifications

Prior to modifying the eartip, the distance d_{ev} – required for the evanescent wave to decay within the EC model – had to be determined. For this purpose, the EC models were terminated by an impedance-matched boundary[1] (i.e. an "absorbing eardrum"), and the SPL variation was simulated along the *z*-axis as shown in Figure 3(I). In this case, the "eardrum" absorbs all the incident energy and only the forward propagating wave travels through the EC model. After estimating d_{ev}, one of the connecting (sound or microphone) tubes was extended by this length.

Figure 3(II) shows the two configurations we intended to analyse. Note that the "eardrum" was simulated as an acoustically rigid boundary in these experiments. In Experiment 1, the active sound-tube port was extended by a length d_{ev}, and the SPL was simulated at the centre of the microphone-tube port (a).

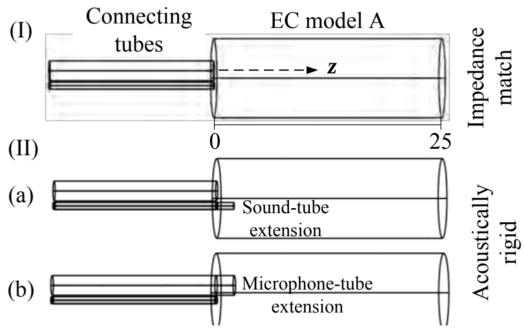

Figure 3. 3D FE model of an OAE probe coupled to (I) an impedance-matched and to (II) an acoustically rigid termination of EC model A. Eartip modifications: extending (a) the sound tube (i.d. = 0.7 mm), and (b) the microphone tube (i.d. = 2 mm).

In Experiment 2, the microphone-tube port was extended by d_{ev}, and the SPL was simulated at the centre of the extended microphone-tube port (b).

3. Results

3.1 Decay length

The EC models were "driven" by source PS and terminated by the impedance-matched boundary condition (Figure 3(I)). Figure 4 shows the SPL variation over the *z*-coordinate (i.e. along the length) of EC model A for five frequencies. The distance over which the evanescent wave decayed was roughly estimated by $d_{ev} \approx 2$ mm.

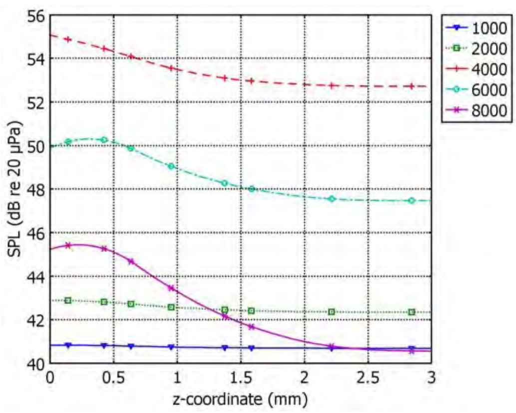

Figure 4. SPL variation along the *z*-coordinate, simulated for five different frequencies. EC model A was driven by source PS and terminated by an "absorbing eardrum".

[1]Alternatively, one may use a perfectly matched layer to determine d_{ev}.

3.2 Probe-tube extensions

The EC models were then terminated by an "acoustically rigid eardrum". Figure 5 shows the SPL results simulated at the microphone-tube ports for EC model A (upper panel) and EC model B (lower panel). In each panel, three SPL curves are shown: (i) without any tube extensions (open circles), (ii) upon extending the sound tube (closed squares), and (iii) upon extending the microphone tube (closed circles).

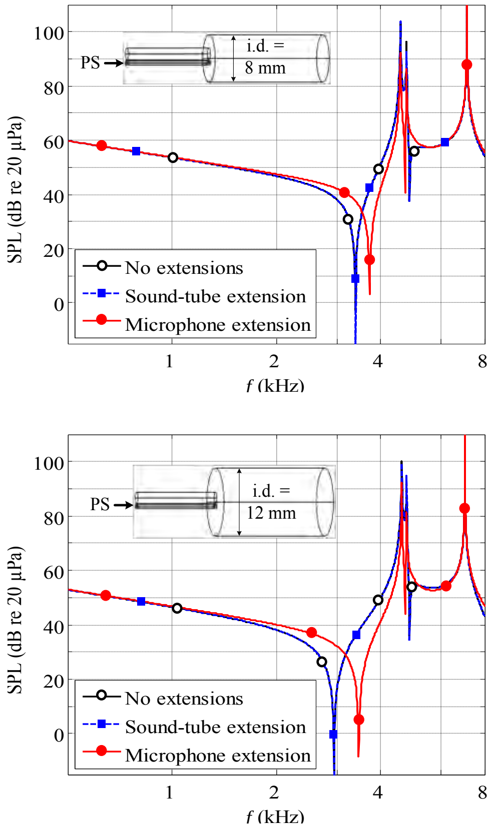

Figure 5. SPL spectrum (in dB re 20 µPa) simulated at the microphone ports of EC models A (top) and B (bottom) for three eartip configurations: no tube extensions (-o-), sound-tube extension (-■-), and microphone-tube extension (-●-).

From the first (quarter-wave) notch frequency f_q the length l_{ac} of a rigid cavity can be "acoustically" estimated as follows:

$$l_{ac} = c/(4f_q), \tag{1}$$

where c is the speed of sound in air. The acoustic length estimations are illustrated by means of an acoustic length diagram (Figure 6). For the exact values of the acoustic lengths, refer to Table 1 in the Appendix.

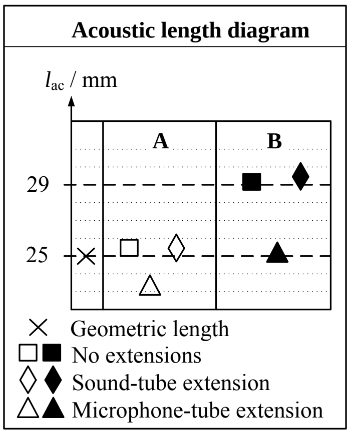

Figure 6. Acoustic length diagram for EC models A (open symbols) and B (closed symbols). Acoustic lengths are given for the following eartip modifications: without any tube extensions (squares), upon extending the sound tube (diamonds), and upon extending the microphone tube (triangles). Geometric length $l_A = l_B = 25$ mm ("×").

4. Discussion

An "absorbing eardrum" allows the sound waves to propagate within the EC models without reflections. Figure 4 shows that the evanescent wave decays rapidly (within about 2 mm away from the probe interface). Hence, a minimum distance for the tube extension was found.

First, let us take a closer look at the SPL curves obtained at the microphone-tube port without any extensions (Figure 5, open circles). While a notch in the SPL curves is expected at the quarter-wave notch frequency of the EC (f_q = 3.43 kHz for a 25 mm-long EC), the notches occurred at $f_{q,A} = 3.35$ kHz for EC model A, and at $f_{q,B} = 2.94$ kHz for EC model B. This shift to a lower frequency can be interpreted as an "acoustic" elongation of the EC models, which was negligible (< 1 mm, "□" in Figure 6) for model A but amounted to approximately 5 mm ("■") for model B. These findings agree with the SPL measurements performed in [4].

Hence, we analysed bypassing this problem for EC model B by extending either the microphone tube (as proposed in [5]) or the sound tube, so as to position its orifice out of the vicinity of the discontinuity. While the extension of the sound tube by 2 mm led to no noticeable improvement, extending the microphone tube (also by 2 mm) was sufficient to compensate for the acoustically over-estimated length of EC model B (refer to the "Acoustic length diagram" in Figure 6).

The most accurate estimation of the EC model length (i.e. the result closest to the physical length of 25 mm, “x” in Figure 6) was achieved without any tube extensions for EC model A (“□”), and upon extending the microphone tube 2 mm for EC model B (“▲”). For both EC models, however, we observed that extending the sound tube had no noticeable effect on the quarter-wave frequency f_q, and hence on the acoustic length estimation (Figs. 5 and 6).

Furthermore, while the microphone extension yielded an improved length estimation of EC model B (“▲” in Figure 6), it deteriorated the length estimation for EC model A (“Δ”). Hence, a microphone-tube extension as performed in [5] is advantageous for the 12 mm-diameter EC model, but is not generally applicable for other EC diameters.

Having analysed the behaviour of the acoustic length on two EC models, the following question arises: Does the acoustic length vary systematically depending on the ear canal diameter? What can we expect should the diameter be less than 8 mm as is the case for baby ear canals? While this remains unknown, it would be interesting for future works to investigate the variation of the acoustic length for a set of EC models having different diameters.

5. Conclusions

In this study, we analysed the impact of minor eartip modifications on the estimation of the acoustic length of an ear canal model. No tube extensions were considered necessary for an 8 mm-diameter ear canal model, whereas extending the microphone tube led to an improved estimation of the acoustic length of the 12 mm-diameter ear canal model. Hence, modifying the 12-mm diameter eartips, by extending the microphone tube 2 mm beyond the eartip termination (as schematically illustrated in Figure 2) may provide a simple way to avoid the effect of the evanescent waves at the interface between the OAE probe and large-diameter ear canals.

6. References

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7. Acknowledgements

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8. Appendix

Data from Table 1 were represented in the “Acoustic length diagram” (Figure 6).

Eartip configuration	**l_{ac} / mm**
No tube extensions	
EC model A	25.59
EC model B	29.17
Sound-tube extension	
EC model A	25.59
EC model B	29.51
Microphone-tube extension	
EC model A	23.28
EC model B	25.04

Table 1. Acoustic lengths of EC model A (d_A = 8 mm) and EC model B (d_B = 12 mm) without any tube extension, upon extending the sound tube, and upon extending the microphone tube, by 2 mm.

Abbreviations

EC: Ear canal
OAE: Otoacoustic emission
PS: Piston source
SPL: Sound pressure level